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THE ROLE OF WOOD MATERIAL FOR GREENHOUSE GAS MITIGATION

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Abstract. Based on an interdisciplinary perspective the role of wood as a carbon sink, as a multi-purpose material, and as a renewable energy source for the net reduction of greenhouse gases is discussed. We synthesize aspects from engineering, natural and social sciences to better understand the role of wood substitution in CO_2 mitigation. We also formulate some recommendations on filling knowledge gaps that could be useful for policy making regarding how wood substitution could be further expanded. There are sufficient wood resources to substantially increase the use of wood for material and energy purposes. However, a number of factors hinder a wider use of wood for energy and material purposes. Furthermore, an analysis of wood substitution is a very complex issue, since the substitution influencing factors are to be found along the entire wood supply chain and involve several industries, socio-economic and cultural aspects, traditions, price dynamics, and structural and technical change. To improve the knowledge about wood as a substitute for other resources and the implications, it would be helpful to better integrate research from different disciplines on the subject and to cover different scales from a project to an economy-wide level.

Keywords: wood, bioenergy, substitution, greenhouse gas emission, policy

1. Introduction

1.1. Relevance of wood for climate change mitigation

A consequence of large-scale combustion of fossil fuels is a build-up of carbon dioxide and other greenhouse gases (GHG) in the atmosphere, contributing to climate change, which is regarded to be both a long-term and large-scale problem (Houghton et al. 1996; Watson et al. 2001a). The United Nations Framework Convention on Climate Change (UNFCCC) resulting from the 1992 Rio de Janeiro conference is the first international, legally binding attempt to tackle this problem. Subsequently, the Kyoto Protocol includes quantified emission reduction targets for the signing parties for the first commitment period 2008–2012 (UNFCCC 1997). The necessary magnitude of the net emission reductions to stabilize the concentration of GHGs in the atmosphere is actually far more than that agreed upon for the first commitment period of the Kyoto Protocol.

Net CO_2 emission has been defined by the Intergovernmental Panel on Climate Change (IPCC) as the difference between emissions from sources and removals by sinks. Thus the portfolio of strategies to mitigate the problem can be divided into two categories: reducing CO_2 emissions or increasing carbon sinks. The forest sector can play an important role in both categories.

Forests are sources of carbon when disturbed as a consequence of fires, insect damage, other reasons for natural mortality, or harvesting. They are sinks of carbon when recovering and regrowing after such disturbances. Carbon stocks are also affected as a consequence of land-use change. Carbon is transferred from forests to products when wood is harvested and used for various purposes. Carbon fluxes in the forest sector can be influenced directly by carbon stock changes in forests or forest products, and by substituting bioenergy for fossil fuels. They can be influenced indirectly by using wood products in place of more GHG intensive materials and products, such as steel, aluminum, concrete, etc. This is actually giving new arguments for wood as a substitute for other materials.

Substitution of fossil fuels provides permanent GHG emission reductions, while sequestration or conservation of carbon is temporary only. Thus substitution allows for a viable transition towards a society that is less dependent on energy and materials that cause higher GHG emissions. Reports from the IPCC have paid considerable attention to carbon conservation and sequestration management, but seemingly less to substitution effects related to the use of wood products that replace products demanding higher levels of fossil fuel inputs (Watson et al. 1996a; 2001a,b).

1.2. Definition of Wood Substitution

We define wood substitution as any use of wood that replaces other inputs of production in providing equivalent service or function. Thus, in the context of this paper wood substitution means increasing the transformation of forest biomass into wood products in order to replace products emitting more GHGs per functional unit. This can be done by making use of:

- wood instead of fossil fuels (fuel or direct substitution),
- wood instead of non-wood materials (material or indirect substitution).

Material substitution of wood involves either *factor substitution* (e.g. in the construction or the chemical industries) or *product substitution* (e.g. furniture, printing paper), meaning that wood can substitute for other materials in a production process or a final product.

For analytical purposes, it is useful to distinguish between fresh forest biomass and recovered wood and fibers (i.e. wood at the end of its first life cycle). Use of fresh forest biomass, in replacing carbon intensive energy and material, has an impact on the forest structure and the carbon balance of the forest, both in the short and longer term. Use of recovered wood and fibers, in contrast, utilizes biomass which has already been lifted out of the *in situ* biological cycle of growth and decay.

1.3. Resource potentials and land use restrictions – general aspects

From the perspective of wood material availability, there is a large potential for increasing wood substitution in Europe, as the current gap between stemwood increment and harvesting is approximately 260 million m^3 per year (TBFRA 2000). While the potential for resources and substitution may vary widely among countries, all European countries have committed themselves to manage their forests in a sustainable way as part of the resolutions adopted by the Ministerial Conferences for the Protection of Forests in Europe (MCPFE 1993, 2003a,b). These are important boundary conditions also from a climate change mitigation point of view. If current harvesting levels are maintained, forests will grow into older age classes, and net increment of wood material will decline (Nabuurs et al. 2002). Conversely, if harvesting levels are increased, age class structures will change towards younger age classes and therefore net increment will increase. From a GHG mitigation point of view, this means that the physical long-term substitution potential will be reduced if the gap between increment and harvest is not utilized.

The above-mentioned technical potential, apart from sustainable yield considerations, may also be increased through intensification of forest management. Examples include optimization of thinning operation, fertilization and choice of tree species. In addition, there are significant areas of set-aside land in Europe that could be, and in fact partly have been, used for afforestation and woody biomass plantations, although there has also been opposition against such changes in land use. Wood production ties up large areas of land for a long time, reducing the flexibility to use it for other purposes. From a carbon balance point of view it is necessary to take into account the reference case for land use to map the full carbon balance.

The supply potential to the market is, however, lower than the technical potential. Reasons include the economic feasibility of resource extraction, preferences and goals of forest owners, as well as society as a whole, considering recreation, conservation aspects and the like. Hence, the demand for certain wood assortments – determined by quality aspects, relative prices, income, established preferences, habits, technological development, etc. – will likely lead to market equilibri that do not fully utilize the technical wood supply potential.

1.4. Aim and scope of the paper

In this paper we discuss the role of wood substitution for reducing net GHG emissions, particularly CO_2, with a focus on indirect substitution. The following six main topics are covered: (1) past and current use of wood to substitute for other materials and energy resources; (2) how to assess different potentials of wood substitution and the contribution of different scientific disciplines to the analysis; (3) methodological aspects; (4) selected case studies related to wood substitution; (5) knowledge gaps; and (6) some recommendations about how these could be filled.

The scope of this article is global with regard to the way wood substitution should be analyzed, but focuses essentially on Europe regarding the examples chosen. We synthesize aspects from engineering, natural and social sciences to better understand the role of wood substitution in CO_2 mitigation. The analysis follows a life-cycle approach, including the end-of-life use of wood products. We elaborate on different potentials of material and energy use of wood to substitute for non-wood materials and fossil fuels, and assess their impact on GHG reduction.

2. The Role of Wood Substitution

2.1. History of substitution

Wood has been a primary energy source for humankind from its infancy. Up to the 19th Century wood was irreplaceable as the most important fuel and raw material for construction, agriculture, crafts, shipbuilding etc. Early shortages of wood have caused both the development of wood saving techniques, e.g. half-timbered constructions in central Europe (Radkau and Schäfer 1987), and the introduction of alternative materials and energy sources. New wood products like paper and railway sleepers and reconstructed wooden materials like fiber and particleboards were developed.

Although other materials have replaced wood in general, wood is still an important material, especially in some societies, such as those in North America and Nordic countries. The average annual per capita use of sawn wood is around 0.15–0.2 m^3 in Europe and 0.5, 0.45, and 0.2 m^3 in USA, Sweden, and Germany, respectively. In contrast, a person in Singapore uses about 0.05 m^3 (UNECE 1996).

Schulz (1993) postulates that the substitution of wood by other materials and energy sources, which is continuing until today, will be reversed and a new phase of re-introduction of wood will start due to environmental reasons and exhaustion of certain non-renewable raw materials and fuels (Figure 1). The future development of wood use appears to be difficult to predict, but GHG mitigation is an important driver, and if suitable policy instruments are implemented, the significance of wood use would probably increase. After the oil crisis in the 1970s wood started to

TABLE I

Materials and products competing with wood (based on Burrows and Sannes 1998)

Materials	Products
Plastics	Packaging, windows and doors, siding, decking, outdoor furniture
Aluminum	Windows and doors, internal decoration, structural members for concrete form work, roof and ceiling coverings, external building decoration (e.g. fences), bridge components, packaging
Steel	Structural material for long-span structures, framing products
Concrete	Construction of buildings and bridges
Gypsum	Wallboards

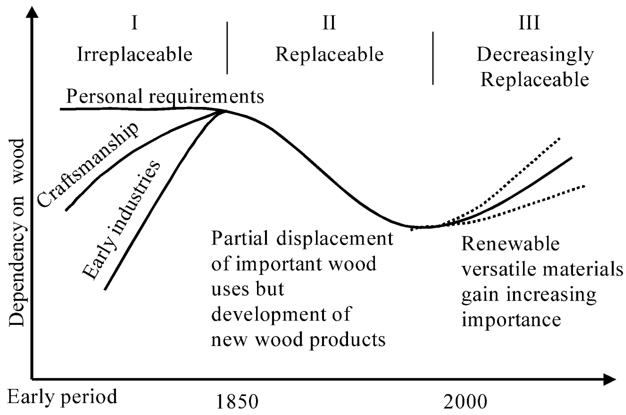

Figure 1. History of wood utilization – Three Phases Theory (Schulz 1993).

substitute for fossil fuels significantly in industrialized countries such as Finland and Sweden.

2.2. Current use of wood materials

The most important materials competing with wood material are plastics, aluminum, steel, concrete, gypsum (Burrows and Sannes 1998) and brick. Steel, concrete, and brick are important alternatives in construction. Aluminum and plastics are widely used in manufacturing of windows and doors. Along with plastics, aluminum is also an important competitor in the packaging sector (see Table I). The competitiveness of wood is challenged in consumer packaging, building cladding materials and framing materials, whereas it is less challenged for example in transport packaging, pallets, flooring and wallpaper (Burrows and Sannes 1998). In many cases, however, different materials may also be complementary, like skeletal structures in office buildings made mainly from wood but also including some concrete in the upper layer.

TABLE II
Share of timber in one and two family house construction in selected countries or regions

Country	Share of timber construction
USA[a]	90–94%
Canada[a]	76–85%
Nordic countries[a]	80–85%
Scotland[b]	60%
UK[c]	20%
Germany[a]	10%
The Netherlands[d]	6–7%
France[b]	4%

Sources. [a]HAF (2000); [b]Reid et al. (2004); [c]Toratti (2001); [d]Kuilen (2001).

Reasons for substitution vary between products and substituting materials. In the following we will discuss the status of wood use and the substitution process in a few selected sectors of the economy.

2.2.1. *Construction Sector*

Use of wood in building construction varies between European countries. Table II reveals that use of wood in the one and two family houses sector is rather low in Europe, except for the Nordic countries. In comparison, wood is dominant in construction of such houses in North America.

In recent years, however, wood has shown signs of increased market penetration in many European countries. For example, in Germany the amount of timber used for one and two family house construction has increased within the last 10 years from 5% (1990) to 10% (2000) (see Figure 2), but still remains at a quite low level. There are large differences between regions within the country and between different types of buildings. The share of timber framed one and two family houses is significantly higher in the eastern part of Germany (15%). Only 2% of all multi-family houses in Germany are built from wood (Statistisches Bundesamt 2002).

Natural conditions have resulted in different building constructions. Building standards and traditions can strongly influence the choice of construction materials and design. Standards and traditions may vary greatly and also change over time between different countries and also between different parts of a country. It appears to be more difficult and take longer to change traditions than standards. Natural conditions may have influence on cultures and traditions. Experiences from World War II in Europe also forced people to look for houses made of materials that increase fire safety. Fire protection measures from that time, including legislative measures prohibiting the use of wood in multi-story buildings, were developed in many areas with high population density. These helped the concrete industry to dominate the building market in Europe, particularly in Central Europe with a

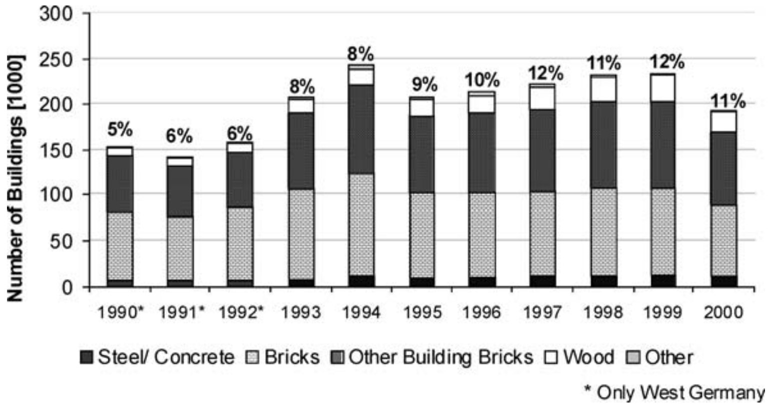

Figure 2. Market share of different materials used in construction of small residential houses in Germany, 1990–2000 (Statistisches Bundesamt 2002). The percentage figures refer to the share of wood material.

market share of about 70–80% (Winter 1995). Shortages of wood for construction have diminished the importance of wood in the Mediterranean zone. Since trade and transportation systems today allow for extensive use of wooden materials outside the forest regions, local shortage of wood does not seem to be the main obstacle any more for an increased use of wood in Europe. There are several other factors, which contribute to the low share of wood in the European construction sector, particularly in multi-story building construction:

1. Wood has a positive image, but asking more deeply about the possibilities of wood utilization, people turn out to be reserved and have developed prejudices against the use of wood as a construction material, based on concerns regarding lifespan, fire security and sound insulation (Rosenbaum 2001). Owners, who decide about the material in building construction, happen to have more faith in concrete than in wood (Bengtson 2003).
2. People see wood utilization as a danger for forests because of the discussions about sustainable forest management, tropical deforestation and the forest dieback in Central Europe (Becker 1992).
3. Building consultants, such as architects and construction engineers, together with building contractors have a key function in the planning process. When their education has been dominated by massive constructions of bricks or concrete they will advise these kinds of construction to interested clients (Renner 1998). Within the construction industry, skill sets are highly diverse. Few constructors have skills, experience and confidence for rapid, high quality timber construction.
4. An investigation of multi-story wooden building construction in Sweden (Bengtson 2003) showed that there are multiple actors involved in the supply of building materials and often they do not maintain long-term co-operations.

Wooden building is still unfamiliar to many and, therefore, the potential of fast building procedures possible with timber frames is not fully utilized. These factors lead to higher cost of construction and delays in project completion.

5. Construction companies hesitate to take the financial risk of building wooden buildings (Bengtson 2003).
6. Fire safety of wooden buildings is frequently questioned and conservative regulations hinder wood construction (Toratti 2001). Östman (1997) has noted that "the wood material's low engineering status is especially striking in the area of fire, where the concept inflammable has been discriminating for a long time and a symbol of the fire risk in wood. In reality wood is, if used in a proper way, a fire safe material with, in some applications, better characteristics than for example steel, which softens and looses its load-bearing capacity even though it is non-inflammable. A more modulated viewpoint is, therefore, needed for the fire technical characteristics of wood as building material".
7. The levels of marketing efforts vary between wood products and competing materials. The wood industry spends less money to educate the public about its products, amounting to only 4% of what is spent by plastic, concrete and steel industries for the same purpose (Burrows and Sannes 1998).
8. Insurance companies put wooden buildings in a higher insurance premium class. The cost for insuring a new wooden building, for example in Germany, is almost double than that for similar concrete buildings in massive construction (HAF 2001).
9. Existing capital-intensive infrastructure and corporate culture may also represent obstacles to change the patterns of use for construction materials (e.g. existing investments and corporate culture in non-wood industries).

It will take time to improve the conditions for the use of wood material and remove barriers. Education of professionals in the construction sector, policy and decision makers, and the general public is an important measure. This education might stress that wood can be used also in multi-story buildings, is a long lasting and renewable material, that fire security of wooden buildings has developed, and that sound insulation has been made effective. Education and promotion of wood have to be based on facts. For example, renewability of wood has to be based on demonstration of management and use of forests in a sustainable manner. Public and state buildings, like the new wooden office building for the Finnish Forest Research Institute in Joensuu (Metla 2004) could be used to inform about innovations in wooden construction.

2.2.2. *Windows and Doors*

The use of wooden windows is more common in the Nordic countries than in other parts of Europe (see Table III). According to Burrows and Sannes (1998), over the last 20 years wooden windows have lost about 75% of the market in Western Europe and the substitution process is still going on, albeit at a slower pace. However, they retain nearly a two-thirds market share in Nordic countries.

TABLE III
Market share of wooden windows

Country/Region	(%)
Nordic countries (reference year not available)	62
Canada (1998)	38
Austria (1997)	33
France (1995)[a]	30
UK (1996)	25
Germany (2000)[b]	23
Spain (average of 1988–1998)	20

Sources. Burrows and Sannes (1998); [a]UNECE (1996); [b]Verband der Fenster–und Fassadenhersteller (2002).

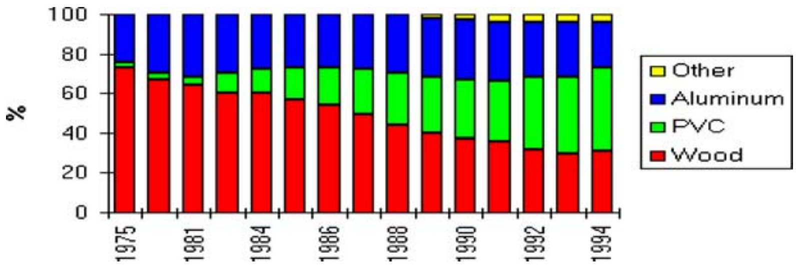

Figure 3. Material input factors in the window frame market in France (UNECE 1996).

The extent to which wooden windows are being replaced by other products varies from country to country. The major part of the substitution comes from PVC and aluminum. In France, for example, the share of wooden windows has decreased from 70% in 1975 to 30% in 1995 (Figure 3). PVC has increased its share from a few percent to 40%, while aluminum has maintained its share of about 20%. Customers prefer PVC windows because they require less maintenance (Burrows and Sanness 1998).

Adoption of wooden window frames depends on regional traditions and type of building concerned. For example, in the north of Germany less than 30% of all windows are made from wood, while in the south the market share of wooden windows is over 90%. In one- and two-family houses, which are mostly privately owned, the share of wooden windows is much higher than in multi-family homes (Mantau 1995). Industrial buildings have mostly aluminum-framed windows.

Recycled plastic composites for outdoor products and plastic façades are very competitive with wood materials. For example, in the United Kingdom, wood, which accounted for 83% of the exterior door market in 1983, lost 25% of market share to PVC and metal by 1995 (UNECE 1996). Currently, in the European residential construction industry about five million tons of plastic are used per year (Nilsson 2001).

2.3. Market studies of material substitution

In the realm of material substitution of wood and non-wood materials, there are mainly three kinds of studies: (1) consumer surveys of market preferences; (2) surveys of actual market shares; and (3) studies of substitution as affected by technology, price and other economic variables, social and institutional factors, etc. Among the surveys of consumer attitudes, Järvinen et al. (2001) studied the perceived preferences among German consumers for wood products, as seen from the perspective of building material suppliers.

Market share studies of the North American building sector document the continued dominance of wood as a building material in North American construction of small-scale residences, and give little evidence of penetration by steel, concrete, or other non-wood systems (Wood Products Council 1999). They point out, however, the substitution among wood products, such as engineered wood products in place of traditional sawn wood, structural particleboard (also known as oriented strandboard) in place of plywood, and laminated veneer lumber in place of large sawn timbers or steel beams.

In the third group are studies of lumber, plywood and oriented strandboard demand (e.g. Spelter 1984, 1985). These show the increasingly advanced or mature state of lumber and plywood in their markets with correspondingly low responses to price changes and, at the opposite end of the spectrum, the relative newness of oriented strandboard with relatively high price sensitivity. Spelter (1995) also documents the relative costs of buildings with various substitute materials.

3. Substitution Analysis

3.1. Substitution possibilities in the wood supply chain

When forest biomass is harvested from the forest, depending on the different assortments, e.g. pulp/fiber wood, logs, tops and branches, the wood might be used to substitute for non-wood materials. From a technical point of view, only certain qualities of wood can be used for specific purposes, e.g. for materials used in building construction or furniture making, while wood residues from felling and/or wood processing operations may be used either for energy purposes or reconstructed materials such as particle boards. Figure 4 illustrates the general material flow of wood among industry sectors. The land where the forest grows could also be included in substitution considerations, which however is beyond the scope of this article.

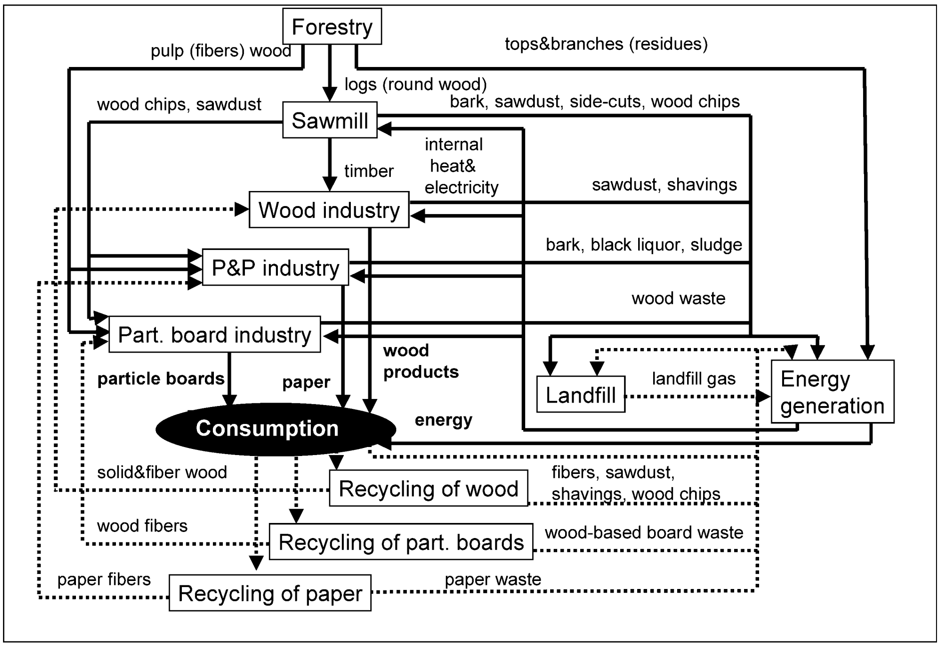

Figure 4. Substitution in the wood chain (adapted from Jungmeier et al. 2002).

Energy substitution takes place if different wood fractions like tops, branches, saw dust etc. are used to produce different energy carriers, such as electricity, heat, and transportation fuel. When this energy substitutes for fossil energy the substitution has a direct effect on greenhouse gas emissions. In many cases the substitution of fossil heat and electricity leads to higher GHG reductions than if transportation fuels are substituted**.**

Material substitution takes place if solid wood products, particleboards etc. are used to substitute other materials and products such as concrete and steel products, gypsum boards etc. This substitution might lead to a reduction of greenhouse gas emissions not only because concrete, steel, and gypsum are more energy and GHG intensive than wood, but also because wood residues from logging and processing and wood-based products at the end of their lives are used for energy generation (Gustavsson et al. 2004).

The treatment of wood-based products at their end of life has important GHG implications. Wood-based products might be landfilled, recovered for other material applications (recycled) or used for energy purposes. Disposal of wood-based products in landfills can have varied GHG impacts. The internal landfill environment is heterogeneous, and many factors influence the production and emission of GHGs. Anaerobic decomposition can produce methane gas that is a more potent insulator but has a shorter effective lifespan than carbon dioxide produced during combustion or aerobic decomposition. However, a part of this methane gas can be collected and used to substitute for fossil fuels. Further, some fraction of the landfilled wood is not decomposed and becomes sequestered in the landfill for a long time. The net GHG impact will depend in part on decomposition conditions within the landfill and utilization of landfill gas in place of fossil fuels. The disposal of recovered wood in a landfill is still a reality in many countries, but is a declining option in the EU because of the actual (EU 1999) or upcoming legislation (EU 2003). Landfilling will therefore not be further considered in this paper.

In the final products markets wood-based products may compete with non-wood products and thus substitute for each other. In addition to the substitution of non-wood materials by wood, there could be inter-wood substitution (e.g. particleboard replaces solid sawnwood).

3.2. GHG ACCOUNTING IN SUBSTITUTION MANAGEMENT

A basic task in a substitution analysis is to choose a relevant functional unit to compare the greenhouse gas emissions from wood use (alternative scenario) with the use of non-wood alternatives (reference scenario). The wood-based alternative should fulfill the same function as the reference scenario. Examples of functional units are a specific product (such as a window), a building component (such as a wall), a complete building, or in the energy field a certain amount of energy (such as electricity, heat, transport fuels). The greenhouse gas emission reduction is then calculated as the difference in the net greenhouse gas emission over the lifetime of the wood and the non-wood alternative. Carbon stock changes as well as the greenhouse gas emissions over time have to be considered. The system boundaries should be set so that all significant changes among the alternatives compared are considered. For example, a difference in land use between wood and non-wood alternatives should be addressed (for further information see, e.g., Schlamadinger et al. 1997; Gustavsson et al. 2000, 2004).

The greenhouse gas emissions could be divided into four different categories of material substitution. First, emissions from fossil fuel use over the life cycle of the products. This includes different steps, such as production, transportation, end-use and waste management of a product. Second, replacement of fossil fuels by biomass associated with wood use. This includes for example residues from logging, wood processing industries, and end-consumers. Third, carbon stock changes in forests and products. Such changes can be complex over time, but in a longer time perspective the changes might be quite limited when sustainable forest management is practised. Finally, greenhouse gas emissions associated with industrial process reactions, such as in cement and steel production. In the substitution analysis, these categories of net emissions should be considered consistently with appropriate accuracy and comprehensiveness.

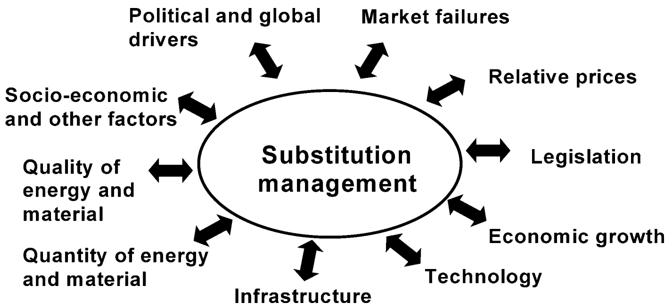

Figure 5. Interdependent criteria for the substitution management.

The most relevant indicators for a substitution management strategy are:

1. Expected amount and time profile of GHG reduction over the life cycle per ton of used dry wood, functional unit or used forest land area;
2. Expected amount and time profile of cost differences over the life cycle per ton of used dry wood, functional unit or used forest land area;
3. Expected mitigation cost, i.e. the cost differences over the life cycle divided with the GHG reduction over the life cycle. The expected cost differences might be expressed as average yearly cost reduction, or discounted to year zero. The GHG reduction will then be expressed as average yearly emission reduction and total reduction, respectively.

3.3. Factors affecting substitution management

Substitution management, which has the greatest mitigation potential in the long term, focuses on the transfer of biomass carbon into products that substitute for or reduce the use of fossil fuels, rather than on increasing the carbon pool itself (Watson 1996b). Aside from the proposition that the same function and service should be provided with wood as with the non-wood materials and fossil energy, there are other relevant substitution criteria. Those criteria are presented in a graphical form in Figure 5 and outlined thereafter:

- *Quality of energy and material:* There are different forms of energy carriers e.g. electricity, heat, transportation fuel etc. The efficiency of converting raw materials to different energy forms varies and, therefore, the substitution potential will also vary. Similarly, quality of wood (characterized by durability, stability in shape, bending properties, grain structure, color etc.) determines the efficiency of wood compared with non-wood materials for building construction, furniture manufacturing etc.
- *Quantity of energy and material:* The higher the total quantity of fossil energy and non-wood material used, the higher is the potential for substitution.
- *Infrastructure:* Transportation facilities are necessary to move woody material from the point of harvest (forest or plantation areas) to the point of use (sawmills

or energy conversion plants). Combustion facilities are required in order to use woody material for energy purposes.

- *Technology:* Technological development, both as new efficiencies in wood use and the development of new products, is important if wood industries are to retain and enhance their competitiveness. Finding new efficiencies in wood use and developing new product designs allow competition on cost and quality. Bioenergy technologies have strongly been developed during the past decades at different scales and along the whole fuel chain. Innovative technologies, such as the gasification technology, are being developed. These developments, along with developments in the fossil fuel based technologies, will determine the ultimate potential of biomass use in the energy sector. In the material substitution sector, investment in technology has resulted in remarkable growth of engineered wood products (EWP) (de la Roche et al. 2003). Production and consumption of EWP has grown well in North America, especially for glulam, I-beams and laminated veneer lumber, all specialty composite construction materials (UNECE/FAO 2003). The factors driving demand for these products have been global competition, decreased availability of large-dimension old timber, new conversion technologies, better adhesive technology and the worldwide adoption of performance-based building codes that allow greater heights and areas for wood construction. However, further processing is not a cure-all solution and can lead to falling company profitability if it is not based on a thorough assessment of material flows, processes, costs, prices and revenues (UNECE/FAO 2003). Technology for multi-story building construction using wood is being developed, and the current market share of wood in this sector is expected to rise in Europe.
- *Economic growth:* Economic theory assumes that demand of energy and material based services increases with economic growth. At present most EU economies are generally based on fossil fuels and non-wood materials. With expansion of the EU, economic growth and income levels are expected to rise in the EU in general, and in Central and Eastern Europe in particular. Even though the specific energy and material utilization is decreasing, the overall energy and material use could increase. Such increased demand would increase the substitution potential for wood based energy and material, provided that biomass (wood) supply is not subject to a binding restriction.
- *Legislation:* Government rules and regulations can have a large impact on the use of wood. GHG emission limits, mandatory purchase of green electricity, restrictions in the use of certain kinds of materials, legal distinction between waste and goods, etc. could facilitate an increased use of wood. At the EU level various directives and policy measures by the European Commission provide incentives for an increased use of wood. For example, the ALTENER program, the White Paper on Renewable Energy Sources and the Directive on Electricity from Renewables encourages bioenergy, the Directive on the Promotion of the Use of Biofuels or Other Renewable Fuels for Transport encourages the use

of biomass for production of transportation fuel. The Commission report on the State of the Competitiveness of EU Forest Based and Related Industries encourages the public to use timber products in construction.

- *Relative prices:* Relative prices between materials influence the market share of different materials. For example, in the absence of full consideration of external costs, electricity produced from biomass is typically more expensive than from fossil fuels. Similarly, the cost of constructing a multi-story building using wood frames instead of concrete or steel might be more costly depending on the local situations. Higher relative price of a material limits its market share. With full internalization of external costs and benefits, wood-based energy and materials would be more competitive However, external costs, particularly those related to GHG emission, vary considerably due to uncertainties. For example, Karlsson and Gustavsson (2003) have concluded that with internalization of GHG emission related external costs biomass-based heating systems are cost efficient in comparison to fossil fuel-based systems for heating of residential houses in Sweden when higher levels of external costs are considered.
- *Market failures:* Insufficient consideration of external costs and benefits is one of the market failures. Trade barriers, market power abuse, and lack of information are other market failures that limit the use of wood. Burrows and Sannes (1998) have noted that while the forest industry promotes wood as an environmentally friendly product, the non-forestry companies portray an impression that forests should be left untouched.
- *Political and global drivers:* Compliance with international laws and protocols, abolition of subsidies and imposition of various taxes on fossil fuels and tax breaks and investment subsidies etc. are some of the political and global drivers of increased use of wood. The Kyoto Protocol is one such example of an international protocol under which the EU has committed to reduce its GHG emission by 8% in 2008–2012 compared to the 1990 level. In order to achieve this target increased emphasis is being put on wood. Emission taxes (such as CO_2 taxes in Nordic countries), investment subsidies (such as for the installation of residential wood pellet heating systems in Austria), green certificates and other such measures facilitate the increased use of wood in the energy sector and the creation of niche markets.
- *Socio-economic and other factors:* Though all the above-mentioned criteria are important, it is actually the consumer demand that indirectly or directly determines the substitution potential. Consumers have typically no direct control over energy and material used, say, in the construction of multi-story buildings. But their opinions may affect the construction companies. In the case of one- or two-family houses consumers can make a decision directly in favor or against a wooden house. Further, they can also choose to buy renewables-based electricity or install a biomass-based heating system at home. Consumer demand, nonetheless, is dependent on socio-economic factors, beliefs, culture and tradition, level of comfort offered by wood-based technologies and products

etc. People who like to support environmentally benign products might like to adopt wooden buildings. However, more often consumers expect materials to meet environmental criteria but are not willing to pay extra (Burrows and Sannes 1998). Multi-story building construction has been introduced recently e.g. in Sweden and Finland, and therefore the costs for such buildings might decrease because of scale effects of construction. People's beliefs about fire safety and acoustic properties of wood also determine acceptability of wood as a construction material. In general, a culture of wood use affects its demand. For example, Scandinavian countries and North America are rich in forests and people use wood in many applications. By way of contrast, in Southern Europe, there is less forest and people are less accustomed to wood use.

The double arrows in Figure 5 indicate that substitution management affects and is being affected by the relevant criteria. Moreover, these criteria are interdependent, e.g., the available infrastructure depends on the legislation and the quantity of material. In analyzing these criteria, it is useful to have an overview of the different substitution management options that have been established in the past and, respectively, that exist today. Further, these criteria might change over time, so an actual assessment of different substitution strategies must be implemented in analyses of effects of, and potentials for, substitution.

3.4. GHG MITIGATION POTENTIALS

There are mainly three different ways of mitigating GHG emission through the use of wood products: wood as (1) a physical pool of carbon (sequestration); (2) a substitute for more energy-intensive materials; and (3) a direct substitute for fossil fuels to generate energy (Karjalainen 1996; Matthews et al. 1996; Marland and Schlamadinger 1997; Apps et al. 1999). The carbon sequestration in wood products depends on an increasing use of wood products in such a way that the carbon content in new products is higher than the carbon losses in the existing wood product stock.

According to the Second Assessment Report of the IPCC (Watson et al. 1996a), the current global stock of carbon in forest products is about 4.2 GtC, while others suggest a stock of 10–20 GtC (Sampson et al. 1993; Brown et al. 1996b). Annual sequestration according to the IPCC (Watson et al. 1996a) is 0.026 GtC/yr, while Winjum et al. (1998) estimated the sequestration to be about five times larger (0.139 GtC/yr). This indicates that there is a large uncertainty in the estimates. But even if the high end of the range is considered, the carbon sequestration in wood products appears small compared to the current rate of carbon sequestration in boreal and temperate forest ecosystems.

Kauppi and Sedjo (2001) have reported that the substitution of industrial wood products may be as large as 0.25 GtC/yr. Assuming a material substitution effect of 0.28 tC/m^3 of final wood product (Burschel et al. 1993) and a roundwood volume of 0.9 billion m^3 annually, this substitution is additional to the sequestration in wood

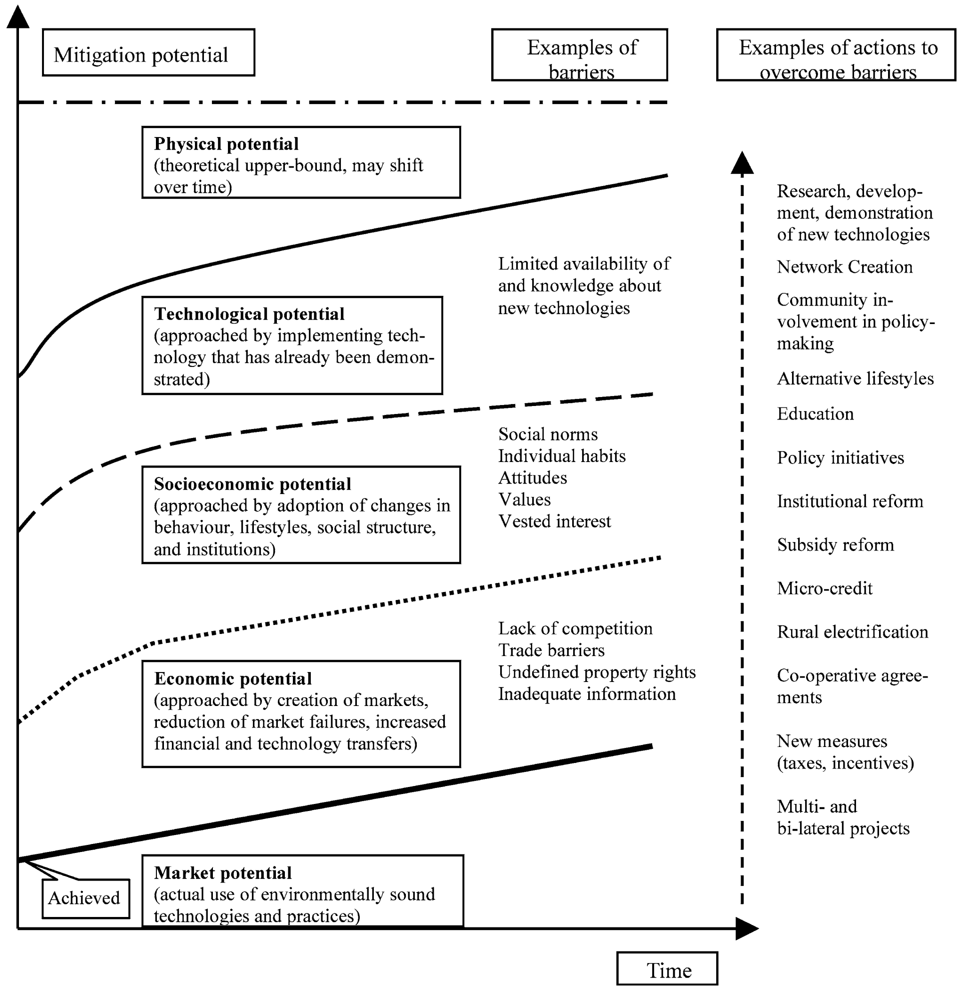

Figure 6. Conceptual framework of different potentials for GHG mitigation (Kauppi and Sedjo 2001).

products. Although this estimate is highly uncertain, it indicates that the substitution impact is larger than the sequestration impact (Kauppi and Sedjo 2001).

The scope for GHG mitigation by means of increased use of wood can be assessed by distinguishing a hierarchy of different potentials (Figure 6). This helps to analytically keep the different potentials separated, and also to discuss the potentials from different disciplinary perspectives.

The *physical potential,* a theoretical upper limit, can be viewed as the GHG mitigation potential that may be reached assuming a complete utilization of the wood biomass and its sustainable growth potential. The *technological potential* denotes the potential that accrues if currently available technology to use wood for material and energy purposes is fully exploited, regardless of the cost, market failures, and socio-economic barriers. The *socio-economic potential* reflects the potential that remains if changes of behavior, lifestyles, social structures and institutions are taken into consideration, while economic viability is neglected i.e., all technologies or measures that are cost-effective from a societal point of view are being implemented. The *economic potential*, in contrast, is the potential that is left if we assume that markets were perfect, i.e., that all cost-effective measures at the individual agent's level are assumed to be implemented. Finally, the *market potential* given by the actual market conditions depends on the decisions of several actors. The decisions of relevance for substitution may be taken by individual consumers or by firms, agencies, corporations, and governmental or intergovernmental bodies. These different agents may act according to different sets of objectives, and may thus act differently to a given change in the environment, both economic as well as non-economic changes. All these aspects influence the market potential. Note that all these potentials, apart from the physical potential, typically change over time.

Assessments of the scope for GHG mitigation through wood use at the different levels can be done with a combination of approaches from different disciplines. Here, we will restrict ourselves to the interplay between engineering, natural, and social sciences, acknowledging at the same time that a number of other disciplines can offer valuable contributions to the knowledge about GHG mitigation potentials and changes thereof. While economic considerations have an influence on all but the top two potentials categories, all technologies and measures have to be technically feasible, and all technologies and measures adopted have certain consequences in terms of GHG mitigation. In other words, it is the combination of all three disciplines that allows for a much more thorough analysis, relative to a purely disciplinary study.

4. Case Studies of Integrated Materials and Energy Use

4.1. Concrete and wood framed multi-family buildings in Finland and Sweden

Börjesson and Gustavsson (2000) and Gustavsson et al. (2004) have thoroughly analyzed, from a life-cycle perspective, how the flow of carbon dioxide is affected when wood construction materials are used instead of concrete. The analysis was based on a new, multi-story building (Wälludden) with a wood frame, located in Växjö in the south of Sweden. In Gustavsson et al. (2004) also a new Finnish building was analyzed. Both buildings are 4-story apartment blocks with a total usable floor area of nearly 1,200 m^2. The wood buildings were compared with similar but hypothetical buildings constructed with concrete frames.

The carbon accounting in these studies included emissions due to fossil fuel use in the production of building materials, the substitution of fossil fuels by biomass residues from logging, sawmilling and building demolition, carbon stock changes in forests and buildings, and cement process reactions. However, energy use for on-site construction, operation and maintenance of the building (e.g. heating), recovery/recycling of non-wood materials and forest soil carbon changes were not included in the analysis. The results showed that production of materials for wood-framed construction required less energy, and emitted less CO_2 to the atmosphere, than production of materials for concrete construction. Furthermore, logging and sawmill residues derived from production of wood-based building materials, and waste wood from building demolition, can substitute for fossil fuels and result in further reduction of net CO_2 emission. Different scenarios were studied. When surplus forest in the case of concrete construction was left untouched, and coal used for electricity production and biomass residues and demolished wood substituted coal, then the carbon emission reduction potentials per dry ton of biomass were estimated to be 0.91 tC/t and 0.62 tC/t in Sweden and Finland, respectively. In comparison, the carbon emission reduction potential was estimated to be 0.45 tC/t of dry biomass when harvested biomass directly replaces coal in power production. This indicates that from a carbon management perspective, the substitution of materials for construction provides a greater emission reduction per unit of wood than substitution of fossil fuels. This is due to the cascading effect where, rather than burning, the harvested wood is used to replace fossil intensive materials in the first stage and the end-of-life wooden material is burnt to replace fossil fuels in the last stage. With respect to per unit floor area the carbon emission reductions were estimated to be 0.057 tC/m^2 in Sweden and 0.13 tC/m^2 in Finland. Over the lifecycle of wood-framed buildings the studies showed that the substitution potential of logging, sawmill and demolition residues was greater than the fossil energy inputs to material production, leading to negative net CO_2 emission. However, the quantitative extent of the difference between wood and concrete framed buildings will vary with the carbon intensity of the fossil fuel considered, and more carbon intensive fossil fuels will increase the benefits of using wood.

The carbon stock of wood products in building construction is of minor importance to the lifecycle net CO_2 emissions of the studied buildings. During the building's lifespan the stock was significant, but over the complete lifecycle the carbon stock change was about zero. If the total stock of wood-framed buildings is expanding, then the carbon stock in the buildings will increase as long as more wood is added through new construction than is taken out due to demolition of buildings. Hence, the permanence of the carbon stock in buildings depends only on the difference between the increase in the amount of wood in new construction and the decrease in the amount of wood from demolished buildings. The only significant stock change occurs when there is a change from concrete construction to wood construction, and to preserve this stock change in the future a wood-framed building must always be replaced by another wood-framed building with a similar carbon stock.

The authors pointed out that there are several uncertainties in the input data used (see also Gustavsson and Sathre 2004). For example, uncertainties remain in accurately portraying the primary energy use of material production, and how that requirement varies with time, place, and process technology. An important topic for future development is also to better understand how wood-framed buildings can be most effectively designed and constructed, subject to architectural and engineering constraints, so as to maximize greenhouse gas emission reduction.

No economic considerations were taken into account in the study. But an indication was given that timber-building technology will be competitive both in quality and economic terms compared with a concrete-framed multi-family building. The question of whether the results could be generalized to other buildings and countries was not addressed in the study, nor were implementation issues considered.

4.2. Material substitution in airport constructions in Norway

Petersen and Solberg (2002) compared the effects for GHG emission of using wooden glulam beams with an alternative solution in steel for the roofing construction at the Gardermoen Airport in Norway. The study was based on a detailed inventory of GHG emissions, including energy use over the life cycle of glulam and steel. The study also provided cost estimates of the input factors used, allowing for the calculation of the cost efficiency.

For the base scenario, the study documents that energy consumption in manufacturing of steel beams is two to three times higher, and the use of fossil fuels 6–12 times higher than in the manufacturing of wooden gluelam beams. Assumptions regarding manufacturing and waste handling had a dominant impact on the results. Assumptions regarding the treatment of carbon sequestration on the forest land regenerated after harvesting, whether the steel production is ore-based or scrap-based, and what kind of energy resources are used for producing the electricity used by the steel industry, also affect the results substantially.

In two other studies also related to the Gardermoen airport, Petersen and Solberg (2003, 2005) analyzed how increased use of wood can substitute alternative materials for construction and covering of floors, and compared GHG emissions, cost efficiency and methodological assumptions. The results show that floor covering with solid oak causes lower GHG emissions than the alternatives, such as wool carpets, carpet in polyamide, vinyl and linoleum. The substitution potential for reducing GHG emission ranks in the following decreasing order: (1) carpet in wool; (2) carpet in polyamide; (3) vinyl and linoleum. By substituting a natural stone floor with a wooden construction, GHG emission can be avoided if the wood is burned for energy purposes after replacement or demolition.

5. Knowledge Gaps and Some Recommendations

The aim of this section is to discuss important knowledge gaps related to wood substitution at different levels of analysis. Three different levels of analysis can be distinguished, which are discussed in the following subsections:

TABLE IV
Relevance of various model and accounting frameworks at different levels of analysis

Modeling/accounting framework	Micro (Actor or project/good level)	Meso (Sectoral level)	Macro (Economy-wide level)
GHG accounting	√	√	√
Engineering-economic models	√	√	√
Econometric models	√	√	√
Partial equilibrium models	–	√	–
General equilibrium models	–	√	√
Input-output models	–	√	√
Technology adoption models	√	–	–
Technology diffusion models	–	√	√
Institutional theory analysis	√	√	√

Note. '√' denotes the levels of analysis where a particular modeling/accounting framework is applicable

- *Micro-level studies*, focusing on individual objects or decision-making entities e.g. on various wood-based products and their substitutes, investor's behavior, GHG life cycles related to a particular product or process;
- *Sectoral- or meso-level studies*, focusing on certain industries or sectors of the economy and restricting the analysis to certain markets e.g. on interfactor or interfuel substitution elasticities, on the supply side, demand side, or both sides;
- *Economy-wide or macro-level studies*, focusing on macroeconomic implications, taking into account all markets e.g. by using input-output models or some kind of partial or general equilibrium models.

In a study describing various aspects of substitution of wood, different modeling or analytical frameworks could be applied to each level of analysis (Table IV). Studies at each level have their own advantages and limitations. However, results from studies at different levels often complement each other, thus providing a richer picture of the complex issue of wood material substitution for other materials than studies using a single approach only.

The three levels of analysis could be put into relation to the five potentials identified in Section 3.4. Note, however, that they are different dimensions, and each of them can be applied to all levels of analysis along the other dimension. In what follows, we discuss the issues that studies on the various levels try to capture as well as the perceived need for further analysis.

5.1. Micro-level studies

Micro-level studies focus on individual actors, projects or goods, and help to better understand the behavior of actors related to the use of wood or, say, the feasibility and impact of a GHG mitigation/wood substitution measure applied to a particular object. Such studies typically use engineering-economic models and may employ a life-cycle approach, for example, to analyze a building construction where wood frames are used instead of steel frames, or in heat and power plants where wood fuels replace fossil fuels. There is ample knowledge about engineering-economic wood energy substitution. However, in applied interfuel econometrics work focusing on micro-data, the research interest so far has been much more on energy substitution than on material substitution issues, so that empirical evidence on material substitution elasticities is still rare.

Specific knowledge about actual material substitution processes (dynamics) at the micro level also seems to be rather scarce. Particularly, for enhancing the existing knowledge it is necessary to carry out more micro-studies that integrate material and energy considerations in a single and consistent framework, such as in Börjesson and Gustavsson (2000) and Gustavsson et al. (2004). Implementation issues appear to be particularly complicated in the construction sector. There is a lack of comprehensive understanding on how to construct a house that (1) has a low GHG emission in the construction phase; (2) causes low emission in the consumer use phase; (3) is affordable; and (4) offers the same comfort level as a house built with non-wood materials. Further, timber construction is still unfamiliar to many and, therefore, the potential of fast building procedures possible with modular timber frames and panels is not utilized. Hence, it is important that the substitution of wood for other materials in the construction sector is understood at the micro-level of the individual decision entities, taking into account a sufficient degree of detail but also the relevant boundary conditions. This is a large area for further research.

Though micro-level models are efficient in projecting an accurate picture of the mitigation potential and related costs at the level of an individual object or project, quite often these models are not possible to be employed due to data restrictions. This is particularly true in the commercial area where such data often are kept confidential. Further, results of a particular mitigation activity in one region or time period may not be extended to other regions or periods, due to spatial and temporal variation of the determinants of wood substitution.

Micro-level studies are very useful in analyzing the reasons behind actors' decisions to adopt a particular GHG mitigation measure. However, less attention has been paid to investigating this area. An example in this category is Bengtson (2003), where the author has carried out an analytical study of the factors affecting penetration of wood as a construction material in the Swedish multi-story building construction sector. More micro-level studies need to be carried out in order to find out the relative importance of the various determinants of consumer behavior, and thereby to help developing policy tools suitable for the diffusion of environmentally more benign technologies. Data on variables related to consumer behavior, such as personal, socioeconomic, and cultural variables, can be collected through surveys and used in empirical technology adoption and diffusion studies, e.g., by means of discrete choice modeling or diffusion modeling, in order to find out the significant factors behind technology adoption decisions and determinants of the diffusion dynamics.

5.2. SECTORAL-LEVEL STUDIES

Sectoral-level studies either focus on the demand side, the supply side, or on both sides of the market for some particular material or product in a particular sector. Models that consider only the demand side include market penetration studies based on epidemic diffusion models such as the Mansfield model (1961) or the Bass model (1969) and variations and further developments of these models. The Bass model has been used to model the diffusion of residential wood pellet heating systems (Madlener and Gustavsson, 2002). These models focus on the technology or product diffusion process only and hence do not include the estimation of GHG mitigation potentials, which however can be estimated by GHG accounting in a complementary way. Supply-side studies consider the biomass supply potential, for example, in replacing fossil fuel in the energy sector. One such example is Börjesson et al. (1997).

GHG mitigation potentials, for example, of wood energy use may be analyzed by taking into account the demand side, the supply side, or a combination of both, and focus on one or several markets along the production chain. Studies of this kind are useful, as they help to determine supply and/or demand functions and elasticities of substitution, and the drivers and dynamics of market diffusion of a particular technology or product. However, they are partial analytical models in that they do not cover all markets or sectors and thus inter-linkages between these markets in the analysis. For example, the biofuel market is closely linked to sectors such as pulp and paper, construction, furniture etc. Market fluctuations along with the impact of policy measures in those closely related sectors would not be captured in the estimation of GHG mitigation potentials through wood substitution in the sector under study.

There seems to be a lack of econometric studies that explicitly consider wood substitution effects, and especially indirect substitution. The main reasons for this include: (1) data restrictions; (2) lack of interest by policy-makers and researchers in the past; (3) imperfect markets that make many models that are based on standard economic theory quite inappropriate; and (4) low shares of wood use. Besides, econometric studies of inter-factor and/or interfuel substitution tend to yield very different results depending on whether time series or cross-sectional data were used. For a useful survey of econometric factor substitution modeling approaches, see, for example Griffin (1993).

5.3. ECONOMY-WIDE LEVEL STUDIES

Studies at the national or supranational level typically try to assess the impact of wood substitution and related policy measures. A better understanding of the substitution effects on all markets of the economy may help to improve policy design. Besides, it is relatively easy to obtain highly aggregated data.

The major drawback of studies on the whole economy, however, is that they use aggregate data and, therefore, obliterate the effect of variables at the micro level. Moreover, these models are of no use in analyzing why consumers differ in their behavior to adopt certain mitigation measures, as the studies typically assume a representative agent (maybe except for multi-agent-based simulation models).

Different types of macro-level models can be distinguished that allow for assessments of wood substitution potentials and effects, such as: (1) top-down models; (2) bottom-up models; (3) input-output models; and (4) general equilibrium models.

Top-down models are usually two-level models. At the first level, demand is made a function of certain explanatory variables (e.g. relative price, real income, technical progress, heating degree days). At the second level, the market shares of the various products studied is made a function of the relative prices of these products, and the outcome is subject to cost minimization. These models assume that economic agents are rational and often yield results on the wood substitution potentials (both in structure and extent) that complement, but usually also significantly differ from those yielded with engineering-economic bottom-up approaches that identify profitable, no-regret investment options. The discrepancy in the model outcomes, but also the largely complementary advantages and disadvantages of the two model families, has led to the development of a variety of hybrid models that aim at integrating these two approaches (e.g. Böhringer 1998; Müller 2000; Koopmans and Willem te Velde 2001).

Bottom-up models at the economy-wide level can help to analyze an optimal use of wood for energy or material purposes based on a linear programming optimization problem. Gielen et al. (2001) is a good example of this modeling approach covering energy and materials use in Western Europe (MARKAL-MATTER model).

Input-output (I/O) models allow the modeling of direct and indirect repercussions of final demand patterns, and have been frequently used to address energy and material use issues. An example of an I/O analysis with an energy-economic model that studies the cost effectiveness of different GHG abatement options is Yoshida et al. (2000).

Economic simulation models and in particular computable general equilibrium (CGE) models can also be useful for assessments of the economy-wide implications of wood use. An example is the Austrian biomass CGE model introduced by Breuss and Steininger (1998), in which they simulate different bioenergy supply scenarios. Bolkesjøet al. (2004) is another recent example, presenting a partial equilibrium model of the Norwegian forest sector (NTM-II). The authors studied the economic competitiveness of forest-based bioenergy products, which they found to depend heavily on characteristics of local energy demand as well as local raw material supply.

Finally, multi-country and global CGE models, and in particular dynamic intertemporal general equilibrium models such as the McKibbin-Sachs Global Model/MSG (McKibbin and Sachs 1989), allow policy and other simulations and forecasting for world regions, or at the global scale (e.g. McKibbin 1998). Such models have also been used widely for the assessment of the GHG mitigation cost (e.g. McKibbin and Wilcoxen 2003). Note that both top-down and general equilibrium models can both be framed as static or dynamic models, and they can be specified as equilibrium (neo-classical economics) models or disequlibrium (Schumpeterian; evolutionary economics) models.

5.4. Some recommendations

In order to better understand the issue of wood substitution and to design suitable policy measures, information is necessary on the actual mitigation potential, the efficiency, and the impacts of various substitution options. However, discussions in the previous sections revealed that knowledge gaps exist regarding various aspects of wood substitution. In order to fill the knowledge gap we outline some recommendations as mentioned below.

- Ample knowledge exists about wood substitution in the energy sector and to a lesser extent about material substitution, especially in the construction sector. Material substitution affects the potential use of bioenergy, but integrated energy and material substitution studies are clearly lacking, especially if implementation issues are to be considered. Hence there is a need for integrated energy and material analyses.
- Wood substitution affects and is being affected by a number factors that might change over time and space. Therefore, there is a need for integrated analysis across different scientific disciplines, in order to estimate the potentials for different substitution strategies and the effects thereof. This includes a better understanding of how to optimize wood substitution in terms of GHG avoidance and costs relative to the services provided, and to give indicative figures and indicators that could be used for rough estimates. In addition, a better understanding is required concerning the sources of variation in GHG balances of wood and other substituted materials, and the extent of variation due to temporal, spatial, and technological differences.
- Implementation studies in the construction sector are mostly lacking. The substitution of wood for other materials in the construction sector, therefore, needs to be better understood e.g. at the micro-level of the individual decision entities, taking in sufficient degree of detail but also limiting the analysis to the relevant boundary conditions. In general, adoption and diffusion studies need to be carried out to identify the significant variables of wood adoption at the individual and society level. Econometric studies that explicitly consider wood substitution effects are also required.

- An efficient wood substitution strategy is closely linked to an efficient transfer of knowledge from research results to practice i.e., to the people who use the knowledge. Hence, there is a need for more targeted dissemination of practical information on wood substitution not only to professionals in trade, but also to builders and engineers, architects, legislators and the final consumer.

6. Conclusions

Climate change mitigation and energy policies aimed at a more sustainable development could more intensively aim at promoting innovative ways of using wood. We have discussed the threefold role of wood as a carbon sink, as a versatile material, and as an energy source that helps to reduce net GHG emission. There are sufficient wood resources for substantially increasing the use of wood for material and energy purposes. Examples from multi-story building construction in Finland and Sweden and airport construction in Norway showed large specific GHG emission reduction potentials by substituting non-wood materials with wood material. However, analysis of wood substitution is a very complex issue, since the underlying system is complex. The influencing factors can be found along the entire wood chain; they include several industries, socio-economic and cultural aspects, traditions, cost dynamics, technical and structural change etc. To improve the knowledge about wood as a substitute for other resources and the implications of such substitution, it would be helpful to better integrate research from different disciplines on the subject, and to cover different scales from a project to an economy-wide level. We have also formulated some recommendations on filling knowledge gaps that could be useful in policy making regarding how existing market potentials could be further expanded.

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